Polypropylene fibres in concrete with regard to durability

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Recent laboratory research has shown that small additions of monofilament polypropylene fibres in concrete, in diameter range of 22 to 35 micron by 19mm long, reduce the flow of water through the concrete matrix by preventing the transmission of water through the normal modes of ingress, e.g. capillaries, pore structure, covercrete, etc. The implications of these qualities in concrete with polypropylene fibre additions is that cement hydration will be improved, separation of aggregate will be reduced and the flow of water through concrete that causes deterioration from freeze/thaw action and rebar corrosion will be reduced, creating an environment in which enhanced durability may take place. As a consequence, lower life cycle costs and best value will be achieved for concrete use, with an ultimate reduction in the cost of maintaining the aging infrastructure. A unique aspect of this work is that heart and covercrete are analysed and compared with corroborative results.

Introduction

It is generally accepted that concrete durability is to a large extent governed by concrete's resistance to the penetration of aggressive media. Eminent researchers and specialists in the field of concrete durability, identifying permeability of the concrete as being a key factor in providing durability, are: Basheer *et al.* (2001), Basheer and Nolan (2001), Figg (1989, 1992), Glasser (2001), Long *et al.* (2001), Roy *et al.* (1990), and Whiting and Walitt (1988).

The significance of this work is such that if polypropylene fibres are universally adopted as a concrete additive, the reduction in maintenance and remedial work to concrete structures will be significant, currently estimated at £550 million pounds per annum for the UK (National Physics Laboratory, 2002), and one to three trillion dollars for all concrete structures world wide (Balendran *et al.* 2002a). Monofilament polypropylene fibres used in concrete provide the qualities of high strength dense concrete without the cost of concrete manufacture associated with high strength/performance concrete manufacture, or the decreased fire resistance due to its increased brittleness (Balendran *et al.*, 2002b). Monofilament polypropylene fibres also provide other qualities that affect durability and these are shown in the Appendix.

Long *et al.* (2001, p. 65) state, "It has been estimated that the value of the infrastructure and built environment represents 50 per cent of the national wealth within most European countries; because of the degree, and rate, of degradation of the built environment in Europe, it is of enormous economic and technical importance". This view is also taken by Mulheron (2001, p. 1) from Surrey University – Civil Engineering Department, who states, "The need to improve our ability to both understand the mechanisms by which deterioration occurs, and the impact that methods of preventing deterioration have on subsequent material performance, is driven by the high cost of maintaining an ageing infrastructure".

It is believed the use of polypropylene fibres will achieve a significant saving on maintenance costs in most climates where regular and severe freeze/thaw cycles occur, with added benefits such as little spalling under extreme fire conditions (Kitchen, 2001) and increased energy impact/resistance with regard to accidental and impact damage (Miller, 1992), also with potential uses in various aspects of design. The purpose of the British Standard 1881, Part 122 test, is to examine the absorption qualities of concrete, in this case with 22 micron diameter monofilament polypropylene fibres, and compare them against a plain control sample as low permeability equates to durability. This philosophy is stated by Mohr *et al.* (2000, p. 1903) "Excellent long term performance in concrete pavements is associated with both concrete strength and durability properties like permeability and chloride ion resistance". Basheer *et al.* (2001) make very similar statements and conclusions.

Concrete core samples were tested for water absorption in accordance with BS 1881: Part 122: 1983. The purpose of this test is to determine the relative absorption values of each concrete type compared against each other, and examine the permeability of the different types of concrete with fibre additions to see if, as predicted, polypropylene fibres block or interfere with the flow of water through the concrete matrix. The methodology behind this test was that the internal structure of the concrete is tested for absorption, which examines the heartcrete. A surface applied test was considered necessary to test the permeability of the covercrete, this will be dealt with as a separate procedure.

Beam and cube manufacture

Four beams were manufactured under test conditions. The beams were one plain concrete beam and three beams with polypropylene fibre addition; the polypropylene fibres used were 19mm monofilament – 22 micron diameter, 38mm fibrillated fibres and 6.50mm monofilament fibres. Cubes were manufactured to the same specification. The concrete specimens were identified as shown in Table I.

Design mix

The design mix was 370kg of ordinary Portland cement (OPC) to BS 12, 675kg of coarse sand; 1,008kg of 20mm gravel to BS 812; with a water cement ratio of 0.5 and a

Table I Classification of specimens in accordance with BS recommendations

Specimen classification	Specimen descriptior
A	Plain concrete beams
B	Concrete beams with monofilament fibres 19mm
C	Concrete beams with fibrillated fibres 38mm
D	Concrete beams with monofilament fibres 6.5mm

fibre addition where applicable of 0.91kg/m^3. The total mass for 1m^3 was estimated to be 2,133kg. It was considered prudent to maintain a minimum WCR of 0.5, as below this value concrete became impermeable and had a natural resistance to water absorption.

Observations taken at the time of manufacture were as follows

The plain concrete when subjected to a slump test (see Plate 1) at WCR of 0.5 collapsed by 227mm, whereas the same mix with the addition of polypropylene fibres failed diagonally in shear and was measured as showing a 120mm slump (Plate 2).

Plate 1 Slump test for plain concrete

Plate 2 Slump test for concrete with monofilament fibres 19mm

The slump test cone was 300mm high (100 per cent) and the percentage slump was 76 per cent and 40 per cent respectively of the height of the cone. This shows that fibres in concrete hold the paste together and increase the thixotropic properties of the fresh concrete. The beams were left for 24 hours after which they were separated from their mould and transferred into a curing tank at 20°C. From examination of BS 8110: Part 1 (1997): structural use of concrete, sub section 6 (BS 8110: 6.2.3.1) "Curing is the process of preventing the loss of moisture from the concrete whilst maintaining a satisfactory temperature regime".

It was clear from the above extract that polypropylene fibres comply with this BS requirement by holding the concrete matrix together in its paste state.

Test method and apparatus used

Three core samples were taken from each beam. Cores were drilled perpendicular to the exposed face for the full thickness of the concrete in accordance with section 4.1 BS 1881: Part 122: 1983. Each core was clearly marked with an identification mark, measured in accordance with BS 1881: Part 122, using a vernier scale, and the specimens were taken to a well ventilated drying oven complying with BS 2648 (see Plate 3). The specimens were left for a period of 72 hours in the drying oven at a temperature of 105°C. The spacing of the samples was checked to ensure 25mm was the minimum space between samples and the walls of the oven.

Plate 3 Dry, marked core samples for absorption test

The samples were removed and each sample was cooled for 24 hours in an airtight container containing silica gel crystals.

Upon removal from the airtight container, the samples were immediately weighed using an electronic balance complying with the criteria as set out in the British Standard. The samples were then immersed in a tank of water at 20°C, with the longitudinal axis of the specimens horizontal and parallel to the base of the tank. The specimens were placed so that a minimum cover of water was 25mm from the top of the cores and they were left in the water for an average period of 30 minutes. Removal of the specimens was started at 29.5 minutes and the last sample was removed at 30.5 minutes; upon removal the samples were wiped with a dry cloth and weighed. Certificates of sampling were not provided other than a manual record of the results for the purposes of compiling the test data.

Water absorption test data

Chronological history – date of concrete production – 11.02.02. Date of absorption tests – 11.03.02 (see Tables II and III).

The mean density of the concrete test samples was 2,256.05kg/m^3.

The mean water content of the concrete test samples was 2.4905 per cent.

Cube A had the highest density, 18kg above the mean, and therefore would be expected to have the lowest permeability. However, compared to the mean water content this cube had a value of 0.145 per cent above the mean, which can be considered to be a high absorption compared to the density and the performance of cube B. Cube B had a density of 0.82kg/m^3 above the mean but a water absorption of 0.1535 per cent below the mean water absorption.

Cube C had a density of 14.02kg/m^3 below the mean density, showing an increased water absorption of 0.1075 per cent.

Cube D had a density of 5.55kg/m^3 below the mean density and an increased water absorption of 0.0605 per cent.

Given that cubes C and D have lower densities than A and B, it could be reasonably expected that the water content would be higher, and this is shown in the results. However, when comparing cubes A and B, it is apparent that cube A has not only the

Table II Test data from absorption tests

Reference	Dry weight (grams)	Wet weight (grams)	Water gain (grams)	Length (mm)	Average diameter (mm)	Dry bulk density (kg/m^3)
A1	1,526.52	1,565.20	38.68	153.50	74.63	2,273.41
A2	1,531.40	1,571.90	40.50	154.60	74.46	2,274.80
A3	1,526.20	1,565.00	38.80	153.40	74.60	2,276.24
B1	1,487.90	1,522.00	34.10	151.40	74.45	2,257.50
B2	1,504.30	1,540.40	36.10	153.10	74.50	2,254.02
B3	1,495.80	1,530.50	34.70	152.30	74.40	2,259.11
C1	1,500.90	1,540.40	39.50	153.50	74.66	2,233.46
C2	1,510.30	1,548.80	38.50	153.90	74.55	2,248.22
C3	1,504.00	1,543.30	39.30	153.60	74.53	2,244.42
D1	1,510.40	1,549.50	39.10	154.00	74.40	2,255.98
D2	1,520.50	1,558.60	38.10	154.60	74.53	2,254.37
D3	1,517.20	1,556.00	38.80	155.30	74.50	2,241.14

Table III Analysis of test data from absorption tests

Reference	Per cent moisture content per sample	Average per cent moisture content per group with average density (kg)	Corrected moisture content (for 75mm sample size)	Comments regarding sample condition
A1	2.534	2.476 m.c. (2,274.80)	3.041	Well compacted and free from voids
A2	2.642		3.170	1 No 6mm dia void
A3	2.254		2.701	As A1
B1	2.292	2.337 (2,256.87)	2.750	As A1
B2	2.399		2.878	As A1
B3	2.320		2.784	As A1
C1	2.632	2.598 (2,242.03)	3.158	As A1
C2	2.549		3.059	As A1
C3	2.613		3.136	As A1
D1	2.589	2.551 (2,250.50)	3.107	As A1
D2	2.506		3.007	As A1
D3	2.557		3.068	As A1

highest density, but also a high moisture content compared to cube B. Cube B has a lower density and also a lower absorption. This must be due to a factor not present in cube A, such as 19mm monofilament polypropylene fibres. Whilst cubes C and D have a higher absorption than A and B, their bulk densities are lower, up to 14.02kg/m, and therefore the moisture content, implying water flow through the concrete, must be lower when compared against the higher density concretes of A and B and their final moisture contents. These test results imply an effect from an added material to the concrete such as fibrillated or short (6.5mm) monofilament fibres, showing that they have a significant effect on moisture flow through concrete.

It has been postulated by many authors such as Knapton and Ellerton (1994, pp. 18-21) and Knapton (2000, p. 10) that monofilament fibres interfere with the bleed channels and capillaries; in addition, Grace Construction Products (1997) commissioned work in accordance with ASTM C232 that show a 45 per cent improvement in hydrostatic permeability, water permeability was reduced between 34-75 per cent (Mather *et al.*, 1987, p. 383), Vondran and Webster (1997) stated, "permeability ... affects durability", which was corroborated by Figg (1989), and finally, Agrement Certificate No. 92/2857 conducted in accordance with BS 1881:5 1970 ISAT and BS 1881: part 122: 1983 indicate that fibres have a small but generally positive effect in reducing water absorption (BBA, 2000).

From these results all fibres appear to show improved water flow resistance, a reduction in the bleed rate and provision of improved consistency. However, monofilament fibres outperform all other additives or fibre types, and this appears to be the case from this test data.

The two batches of concrete A and B, and C and D, were of different densities – the 19mm monofilament fibres have a lower density, which might imply an air entraining effect, therefore somewhere for the hydraulic pressure to go, when compared to plain concrete. This aspect is worthy of further research and investigation.

From examination of BS 8110: Part 1: 1997: Structural use of concrete: 3.1.5.2 Design for Durability, comment is made "Since many processes of deterioration of concrete only occur in the presence of free water, the structure should be designed, wherever possible, to minimise uptake of water or exposure to moisture". This statement particularly applies to the effect polypropylene fibres have in restricting water flow through the set concrete, and therefore the inclusion of polypropylene monofilament fibres will help ensure the requirements of BS 8110 are met with regard to durability.

Covercrete testing

After 35 days from production, air dried 150×150×150mm test cubes were soaked for nine days and removed from the curing tank, the absorption results are shown in Table IV.

It is clear from the results that the overall absorption is relatively low and this may be due to the size of the concrete sample being tested, however, it is also true that the samples were air dried, prior to re-hydration. The distance water has to travel through the cube is also a key factor as the section length is double that of the core tests, therefore the lower figures are predictable, as it is generally accepted that absorption is only effective to a depth of 50mm, thereafter different transport mechanisms are used. A further consideration is that 19mm monofilament polypropylene fibres in concrete hinder the absorption of water ingress at a significant rate compared to plain concrete and other types of polypropylene fibres. This test indicates that the use of 19mm monofilament polypropylene fibres is very effective in reducing the absorption of water through the covercrete in comparison to the first series of tests using core samples.

Table IV Absorption results for test cubes

Reference	Dry weight (grams)	Wet weight (grams)	Water gain (grams)	Per cent moisture content at "100 per cent" saturation
A	7948	8048	100	1.26
B	7977	8058	81	1.02
C	7959	8065	106	1.33
D	7915	8015	100	1.26

Summary

In summarising the section on absorption, it appears reasonable to presume polypropylene monofilament fibres, in small quantities, have a "log jam" effect with regard to the flow of water through the concrete matrix, by preventing the transmission of water through the normal modes of ingress. The implications of these qualities in concrete with polypropylene fibre additions is that cement hydration will be improved, separation of aggregate will be reduced and the flow of water through concrete that causes deterioration will be reduced, creating an environment in which enhanced durability may take place.

The BS test as described removes the likelihood of polypropylene fibres creating an impermeable laitance of covercrete as the cores ensure the heartcrete is tested. From the fibres tested, it is the author's opinion that 19mm long monofilament fibres in the region of 20 to 35 microns in diameter will be most efficacious in reducing the flow of water into concrete, thus providing enhanced durability at a very reasonable price per m^3. An extract from Agrément Certificate No. 92/2857 states, "initial surface absorption tests (ISAT), conducted in accordance with BS 1881:5: 1970, water absorption to BS 1881: part 122: 1983 and results of other tests on concrete cores, indicate that the fibres have a small but generally positive effect in reducing water absorption" (BBA, 2000). It is the author's opinion that this work corroborates the Agrément Certificate and extends the understanding of how monofilament polypropylene fibres prevent water from penetrating concrete, particularly when examining the full cube absorption test in tandem with the core test.

Resistance to permeability and increased toughness of concrete is enhanced by using monofilament polypropylene fibres, and this study forms part of the equation, shown in the Appendix, which outlines the factors affecting durability and the effect that polypropylene fibres play in providing enhanced durability through resistance to migration, absorption, mechanical bonding, etc. A quality of polypropylene fibres not investigated herein is one of fire resistance, with regard to preventing spalling of *in situ* concrete (Kitchen, 2001). The fire resistance ability of polypropylene fibres in concrete is an attractive quality when considering structural members in buildings following the 11 September World Trade Centre attack.

In 1979/1980 tests were carried out at the Building Research Establishment to determine the effects of age on polypropylene fibre reinforced concrete (Hannant, 1998). It was found when samples were left to encounter natural weathering, a reduction in strength occurred between five and ten years, however, the 18 year strength was identical to the ten year strength (Hannant, 1998). It was further concluded that it was unlikely that the composite will ever become brittle due to excessive bonding and that the bond strength between cement and polypropylene as calculated from the test results was relatively unaffected by exposure conditions for time periods up to 18 years. Hannant (1998) concludes in his paper that, "Overall the composite has been shown to retain its toughness and strength at a high level over many years, giving increased confidence in the long term stability of polypropylene in a cementitious environment". Mu *et al.* (2002), who conclude, "polypropylene mesh is less expensive and has no aging problems", concur with Hannant.

Monofilament polypropylene fibres are responsible for enhancing durability and providing a potential for lower life cycle costs, thus saving huge repair bills, whilst maintaining the fabric of our concrete infrastructure and providing the best value with regard to concrete cost compared to that of durability.

The problem with any study of aspects of concrete performance is that concrete is five different component parts acting individually and yet acting together, therefore a precise conclusion as to exact performance will rarely be possible due to the large degree of variables. Therefore the best scenario with regard to the outcome of current laboratory results is that of identifying a trend that leads towards durability. It must not be considered the addition of polypropylene fibres will compensate for poor design, as lack of durability is generally a combination of many factors, as shown in the Appendix, however, water absorption is a significant factor and the degree of impedance to water flow is sufficient to make fibre addition a serious consideration for the designer when planning the life of a structure. Given the extreme environmental pressures that will be brought to bear over the next few decades, enhanced durability will be a key component in providing the designer with a cost effective design option, and in this regard monofilament polypropylene fibres will play their part.

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Further reading

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Appendix

Equation for durability (1)

$$D = \sum f(A + PR + FS + PO + IF + C + TC) + (WCR + MF + AE + S + E)$$

D = sum of the effects of polypropylene fibres plus the concrete type, set in the environment (serviceability limit state design will design durability into the structure due to very small crack widths and predetermined stress levels).

Where:

- D = durability
- A = absorption qualities (capillary and pore structure)
- PR = pressure relief (density of polypropylene – density of concrete)
- FS = flexural strength mainly from the use of fibrillated fibres (bond)
- PO = pull out values, mainly from fibrillated or crimped/structural fibres (bond between fibre and cement)
- IF = ion flow mainly from monofilament fibres (impedance/resistivity)
- C = consistency of mix (aggregate dispersion)
- TC = thermal conductivity (reciprocal of conductivity)
- WCR = water cement ratio
- MF = micro filler (pozzolanas)
- AE = air entrainment (pore size and per cent voids and distribution)
- S = crushing strength (N/mm^2)
- E = exposure conditions.

The a priori equation needs further development set against empirical data to achieve a value at which prescriptive durability criteria for concrete in service can be predicted.

Whilst one of the above qualities within the equation may not provide a significant increase in durability, the combined effects of these qualities when using polypropylene fibres have a significant effect on the durability of concrete irrespective of the strength and mix type, however, when mix type and service environment are taken into account an overall assessment of the likely performance can be fairly evaluated.

Water and aggressive chemicals are transported into the "covercrete", then into the heartcrete by various methods, these being via the cement paste matrix or micro cracks in a physical sense, and this is a primary cause of concrete degradation.

In addition, there are a variety of physical and chemical mechanisms that will govern the transport of water, including chemical solutions. These are diffusions, permeation, capillary suction, absorption, adsorption and migration. "There is a body of opinion advocating the use of water and gas permeation properties of covercrete as durability indicators and terms such as permeability, sorptivity and diffusion are used in this respect" (McCarter *et al.*, 2001, p. 2). This view is corroborated by Karr *et al.* (1997) who state, "Cracks in concrete generally interconnect flow paths and increase permeability. The increase in concrete permeability due to the progression of cracks allows more water or aggressive chemical ions to penetrate the concrete, facilitating deterioration." Serviceability limit state applied to design must be a key factor in reducing crack width and therefore increasing durability. Monofilament fibres reduce the tendency of concrete to absorb water and therefore provide enhanced durability.